Simulating building energy efficiency impact potential:

From individual occupants to the national building stock

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About me

- Ph.D., Architectural Engineering from Drexel University
- B.Arch. from Carnegie Mellon University
- 2014 - DOE Building Technologies Office (BTO) EERE Science & Technology Policy (S&TP) Fellow

Roles as an EERE S&TP Fellow in BTO:

- Lead technology impact analysis (co-developer of Scout)
- Co-lead the BTO Catalyst Prize Program
- Support Sensors and Controls program funding and planning
- Proposal review (BTO, ARPA-E), workshop planning
- Quadrennial Technology Review Buildings chapter

What we'll cover

Simulation programs that enable better decision-making about energy efficient building design and operation at multiple scales of focus

Part 1: Building occupant scale - HABIT
Software for estimating the occupant-level Indoor Environmental Quality (IEQ) and energy use impacts of building operation strategies, given realistic occupant behavior

Part 2: National building stock scale - Scout
Software for estimating the national energy and carbon savings impacts of building energy efficiency measures

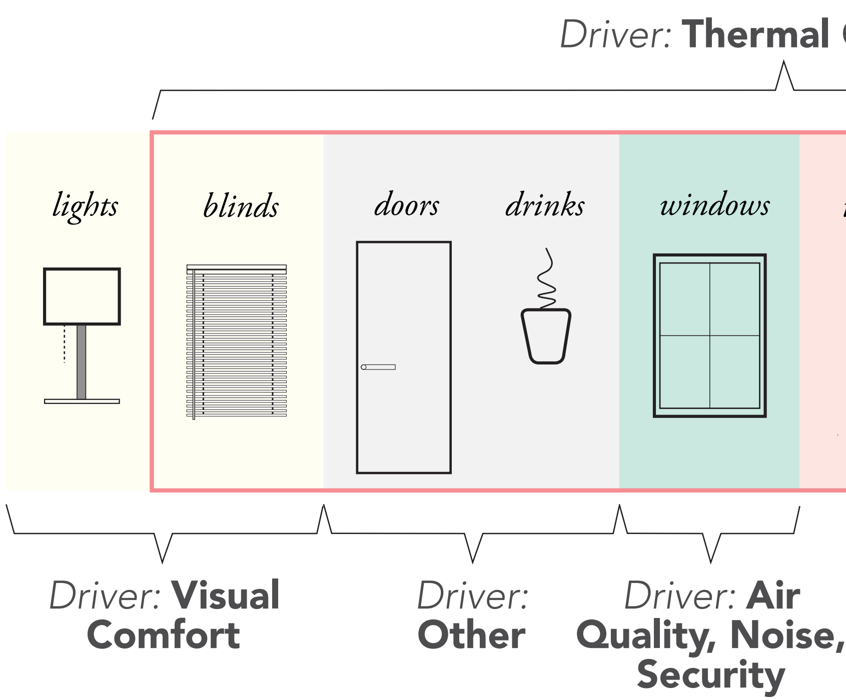
Part 1

HABIT: A framework for occupant behavior, comfort, and energy co-simulation

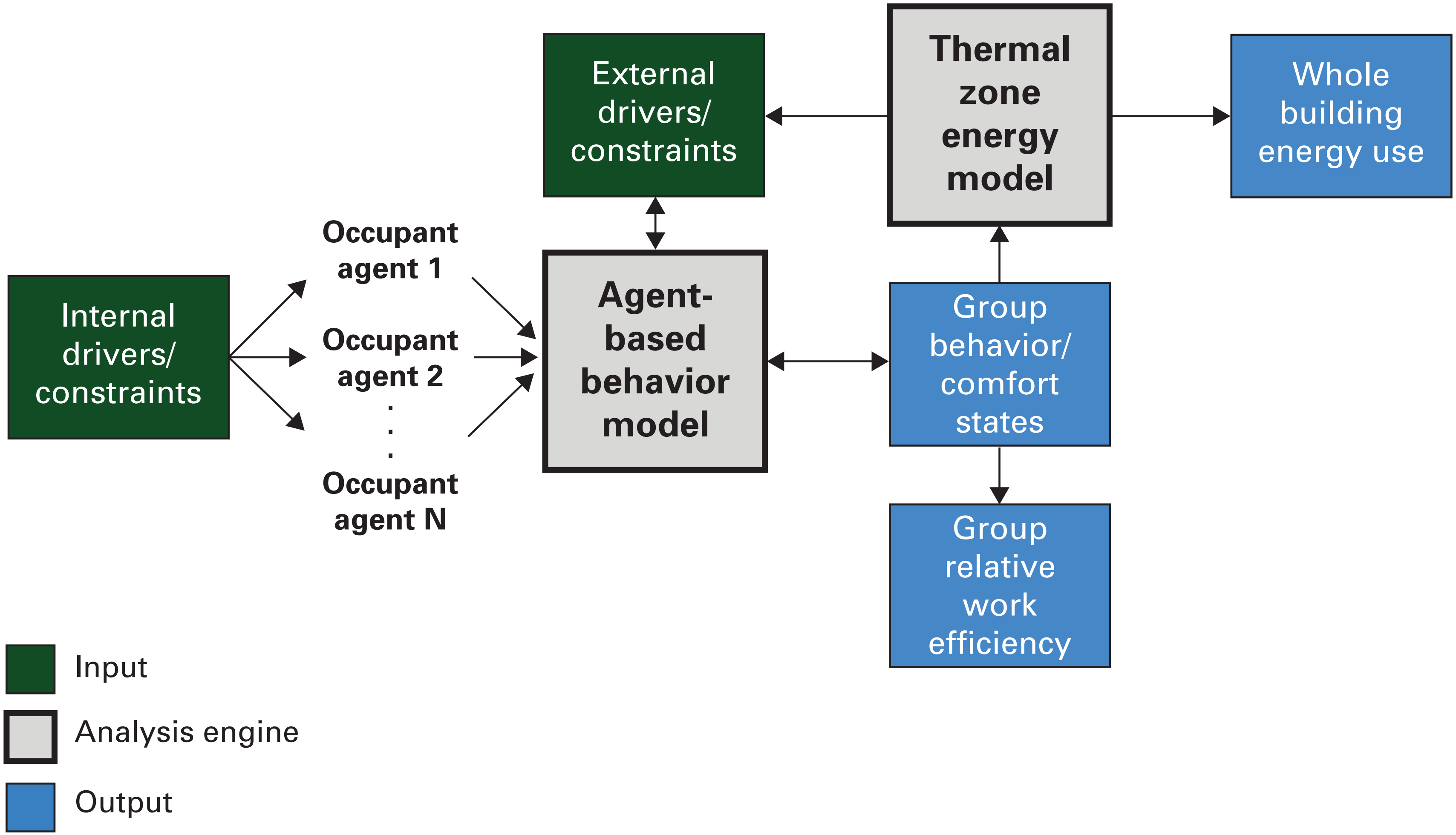
Ph.D. thesis work performed at Drexel University under advisor Dr. Jin Wen, with funding from a National Science Foundation Graduate Research Fellowship

The problem: occupants affect building performance but are not easily modeled

- Occupants' behaviors are at the energy/IEQ nexus
- Behaviors have many possible drivers, vary by context
- Existing behavior models are mostly 'top-down', group-level, and only consider external drivers (e.g., temperature)



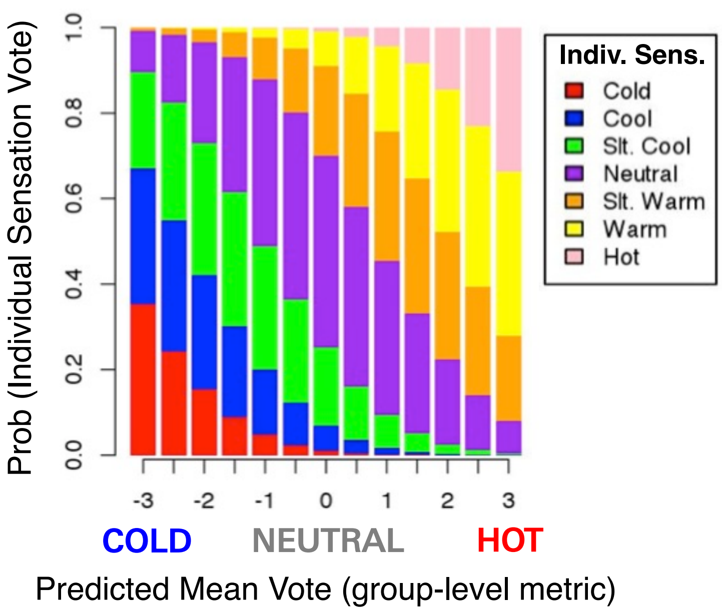
HABIT represents behavior from the bottom up, at the individual level



Individual-level thermal sensation and acceptability models are developed

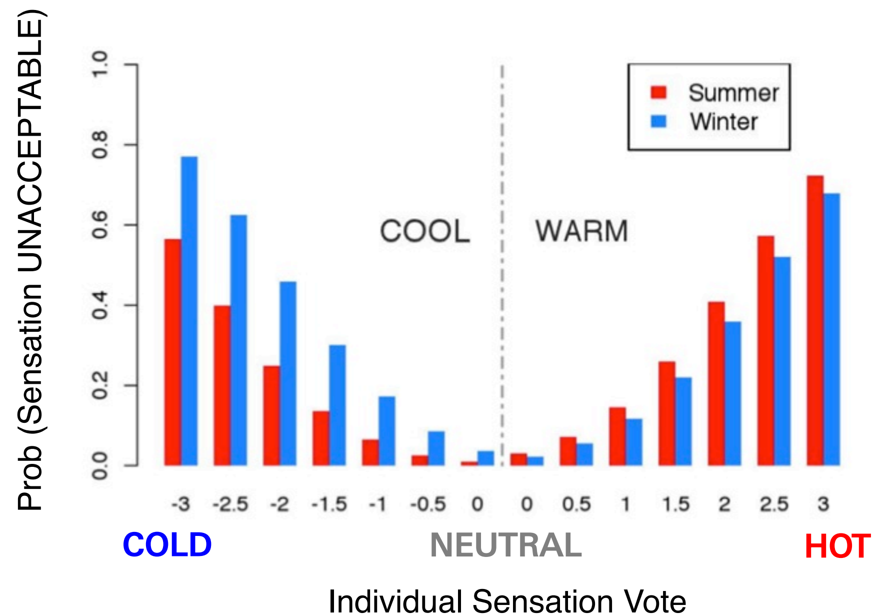
Thermal sensation distribution

Prob (individual sensation vote) = f(Predicted Mean Vote)



Thermal acceptability distribution

Prob (individual sensation unacceptable) = f(individual sensation, season)

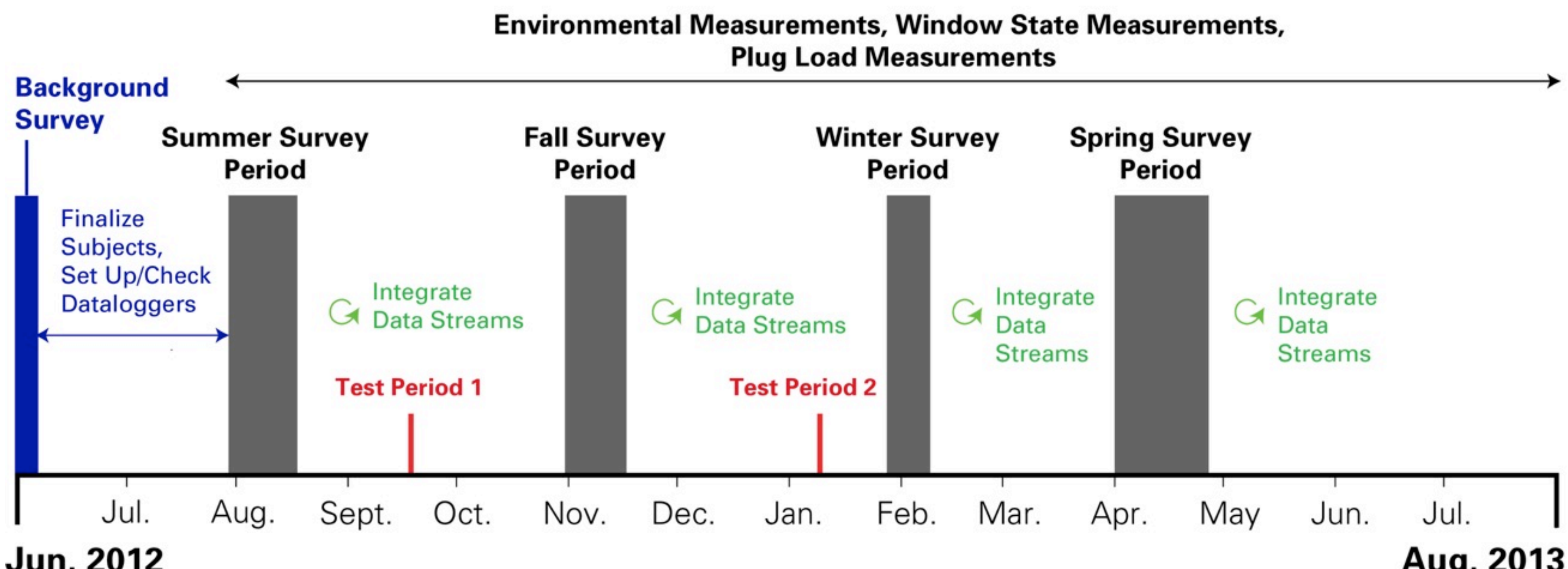


Langevin et al, “Modeling Thermal Comfort Holistically”, Building and Environment, 2013

Long-term thermal comfort and behavior outcomes are observed in the field

The Friends Center, Philadelphia, PA

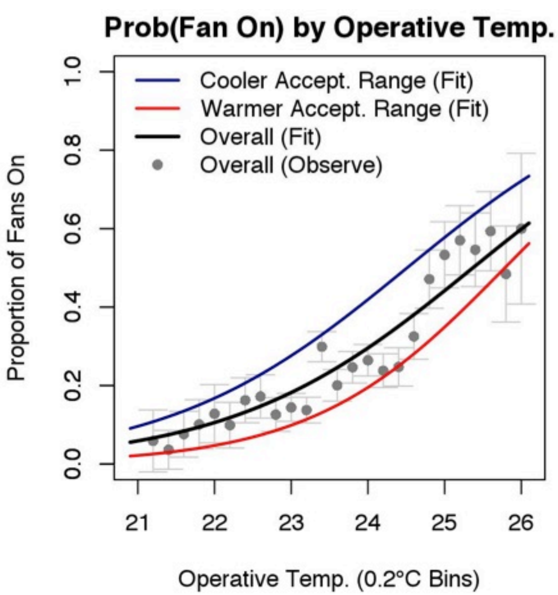
- LEED Platinum (2009), medium-sized air-conditioned
- Range of behaviors, Building Monitoring System
- Final sample: 24 occupants



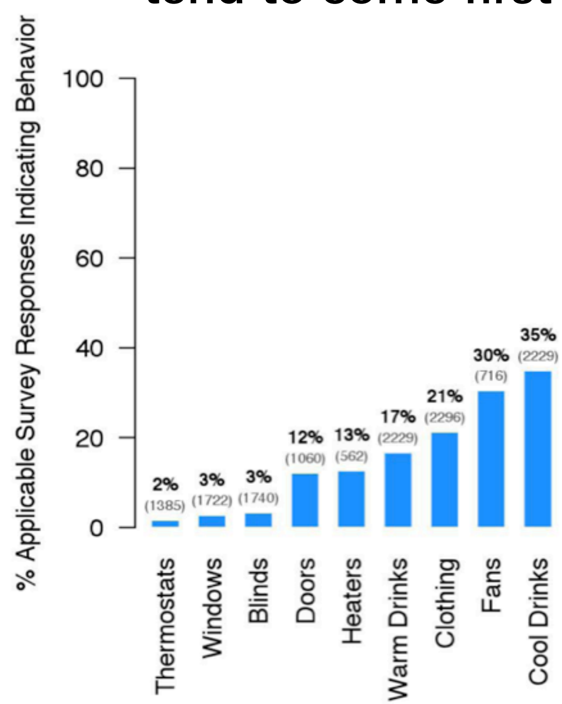
Langevin et al, "Tracking the human-building interaction", Journal of Env. Psychology, 2015

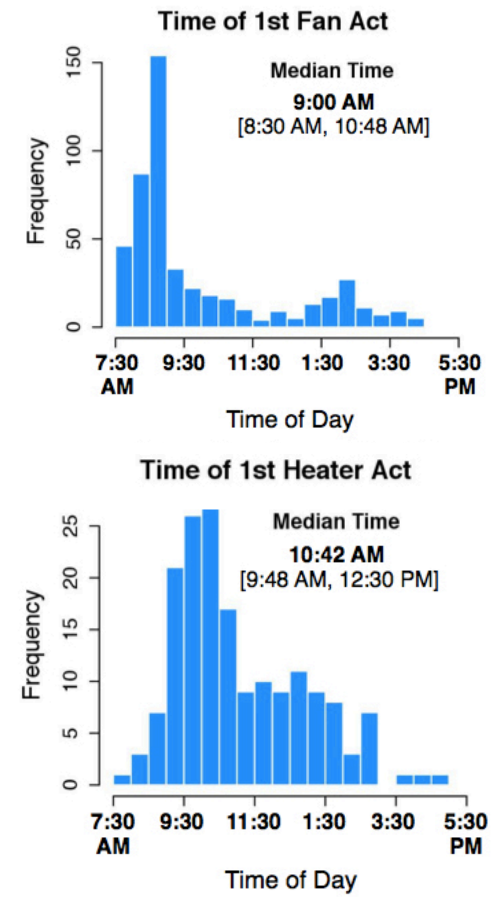
Behavior associates with thermal acceptability range and is sequenced

Those with cooler acceptability ranges are more likely to execute 'too warm' behaviors



Easy, more immediate behaviors tend to come first

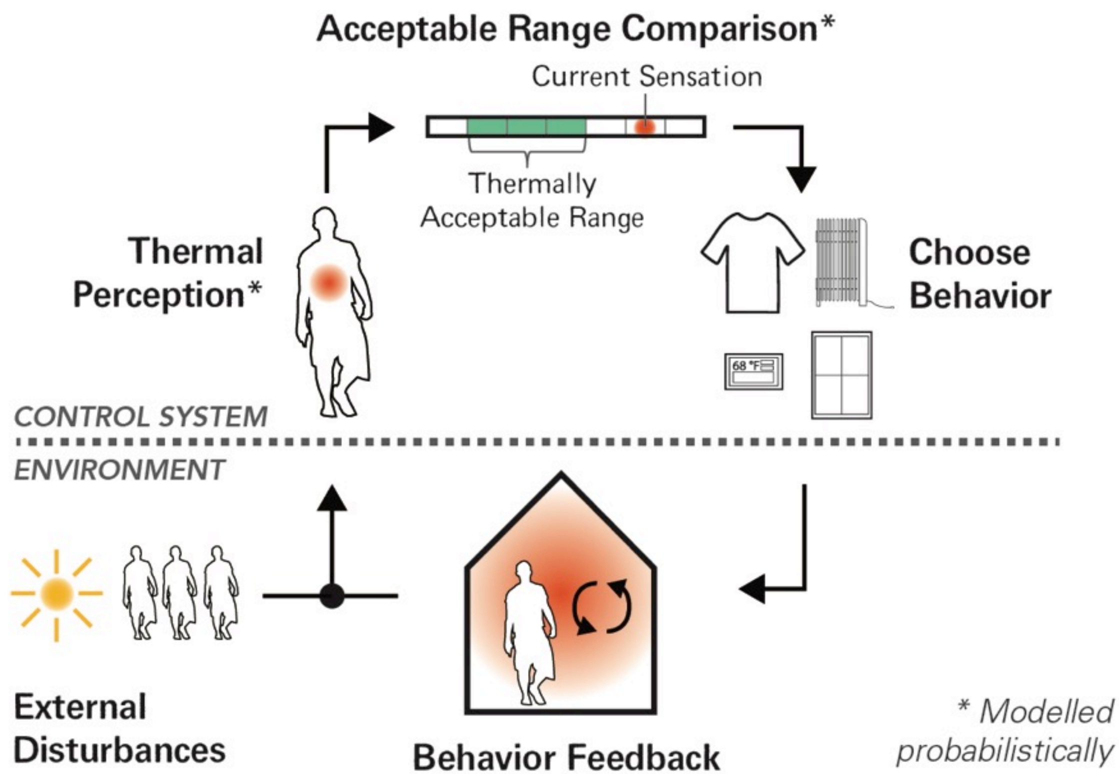




Langevin et al, "Tracking the human-building interaction", Journal of Env. Psychology, 2015

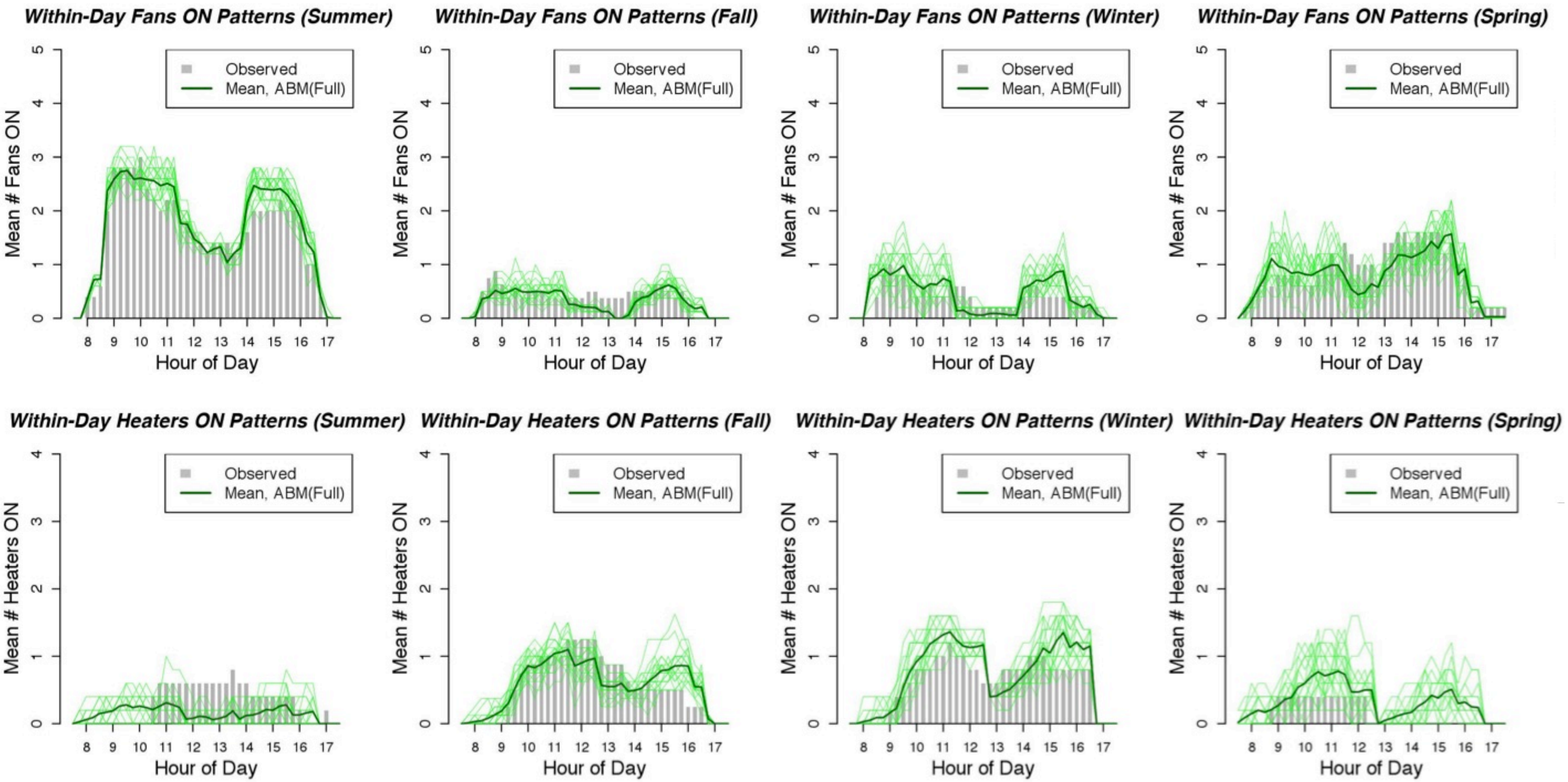
Field findings and individual comfort models inform an agent-based model

- Individual occupant = simulated "agent"
- Behaves according to Perceptual Control Theory (Powers, 1973)
- Behavior constraints and hierarchy
- Outlined using ODD description protocol for agent-based models (Grimm et al, 2010)



Langevin et al, "Simulating the human-building interaction", Building and Environment, 2015

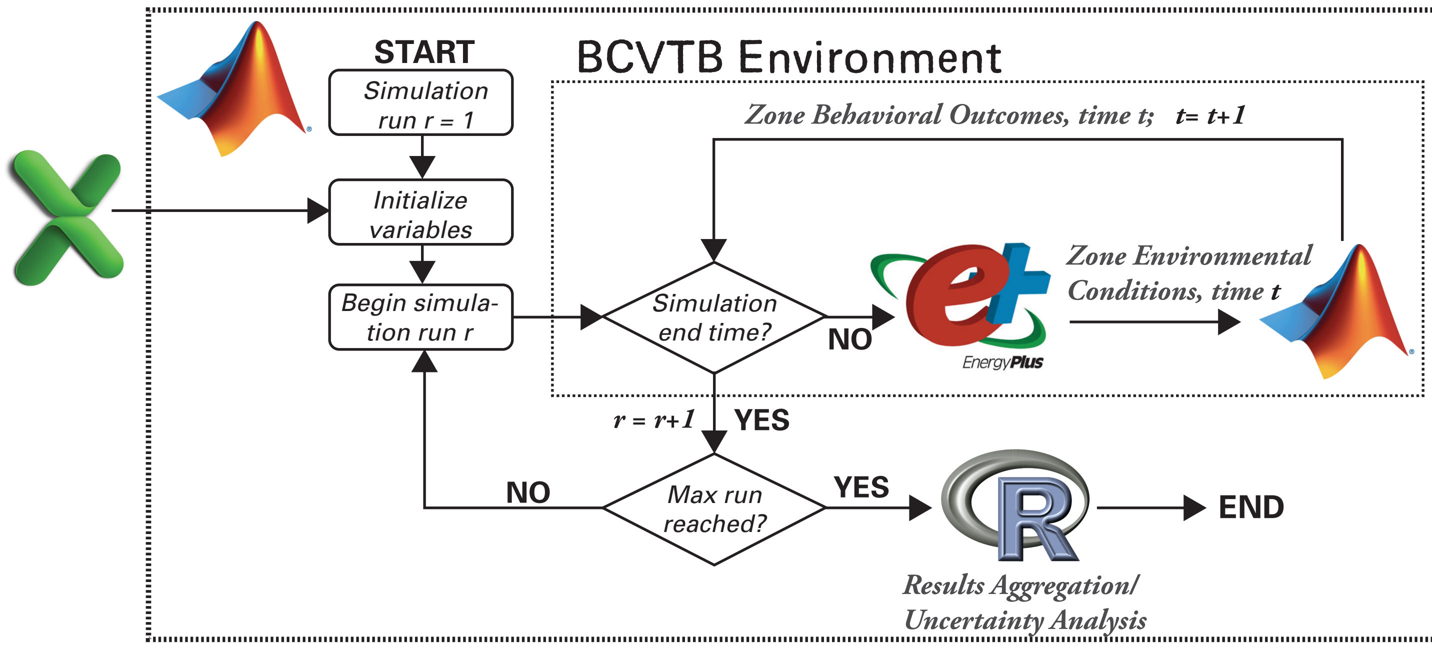
The agent model performs well against field data, other behavior models



Langevin et al, “Simulating the human-building interaction”, Building and Environment, 2015

The behavior model is co-simulated with a whole building energy model

- BCVTB co-simulates behavior and EnergyPlus models
- Each run repeated multiple times (probabilistic elements)
- Simulation is configured from an Excel spreadsheet



Langevin et al, "Quantifying the human-building interaction", Energy and Buildings, 2015

The HABIT behavior/energy co-simulation tool has multiple use cases

- Prospective building design and operation
  - Near-term application: behavior and IEQ factored into whole building energy simulations
  - Long-term application: Model Predictive Control of occupant-centered sensor networks
- Building efficiency policy making
  - Near-term application: Quantifying stock-wide energy/CO_2 benefits of behavior efficiency measures
  - Long-term application: Quantifying stock-wide non-energy/CO_2 benefits of behavior efficiency measures (e.g., productivity costs)

A HABIT case study: The energy, IEQ, and cost implications of wider set points

- Run seven behavior scenarios on EnergyPlus medium office reference model; last four widen thermostat set points
- Simulated with Philadelphia weather file for January and July

#	Name	Clothing	Fans	Heaters	Thermst.	Window
1	Baseline *(B)*	N/A	N/A	N/A	N/A	N/A
2	Restricted *(R)*	–	+15 W	+1200 W	21; 24ºC[1]	+25X infil.
3	Unrestricted *(UR)*	–	+15 W	+1200 W	21; 24ºC	+25X infil.
4	Wider Set Points *(WSP)*	–	+15 W	+800 W	20; 27ºC	+25X infil.
5	Wider Set Points + Educate *(WSPe)*	–	+15 W	+600 W	20; 27ºC	+25X infil.
6	Wider Set Points (Moderate) *(WSP2)*	–	+15 W	+800 W	19; 28ºC	+25X infil.
7	Wider Set Points (Extreme) *(WSP3)*	–	+15 W	+800 W	17; 30ºC	+25X infil.

1 Shown are heating set point in January; cooling set point in July.

Unrestricted w/ education
Unrestricted completely
Restricted by management
Restricted by management + others in space

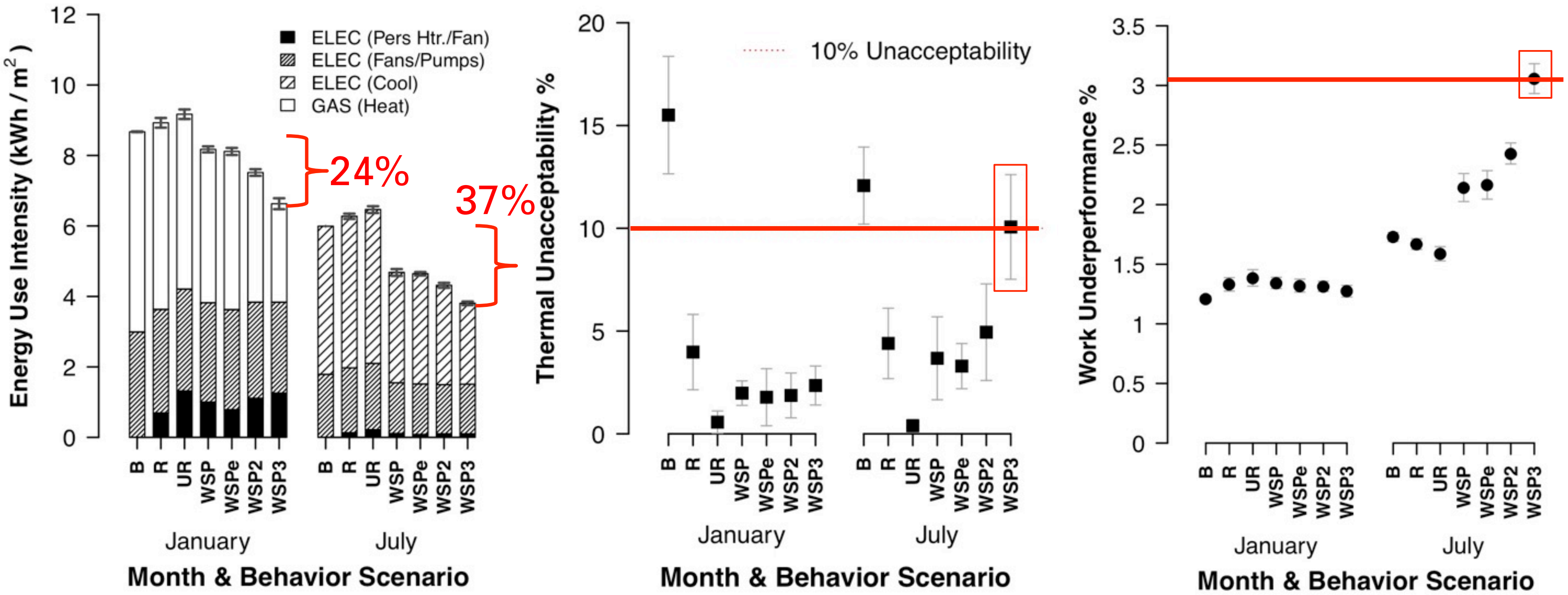
Langevin et al, "Quantifying the human-building interaction", Energy and Buildings, 2015

Case study outputs span energy, IEQ, and cost-benefit categories

Category	Metric	Calculation
Energy	Energy Use Intensity **Note**: HVAC + personal heater/fan use	$kWh/sq.m.$
Comfort	% Thermal Unacceptability	$\frac{\#\, Time\ Steps\ Uncomfortable\ w/\ no\ Remedy}{Total\ \#\, Time\ Steps}$
Productivity	% Work Underperformance **Note**: warmer = suboptimal	$100 - Relative\ Performance\ \%$ (Jensen et al, 2009)
Cost-Benefit	Net Present Value (NPV) - 10 yr.	$\sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$
	NPV1 *NPV2* *NPV3* **Note**: + 1% annual underperformance ~ $75,000	*Energy $* *Energy + Carbon $* *Energy + Carbon + Productivity $*

Langevin et al, "Quantifying the human-building interaction", Energy and Buildings, 2015

Wider set points look good from the energy and IEQ perspectives - to a point



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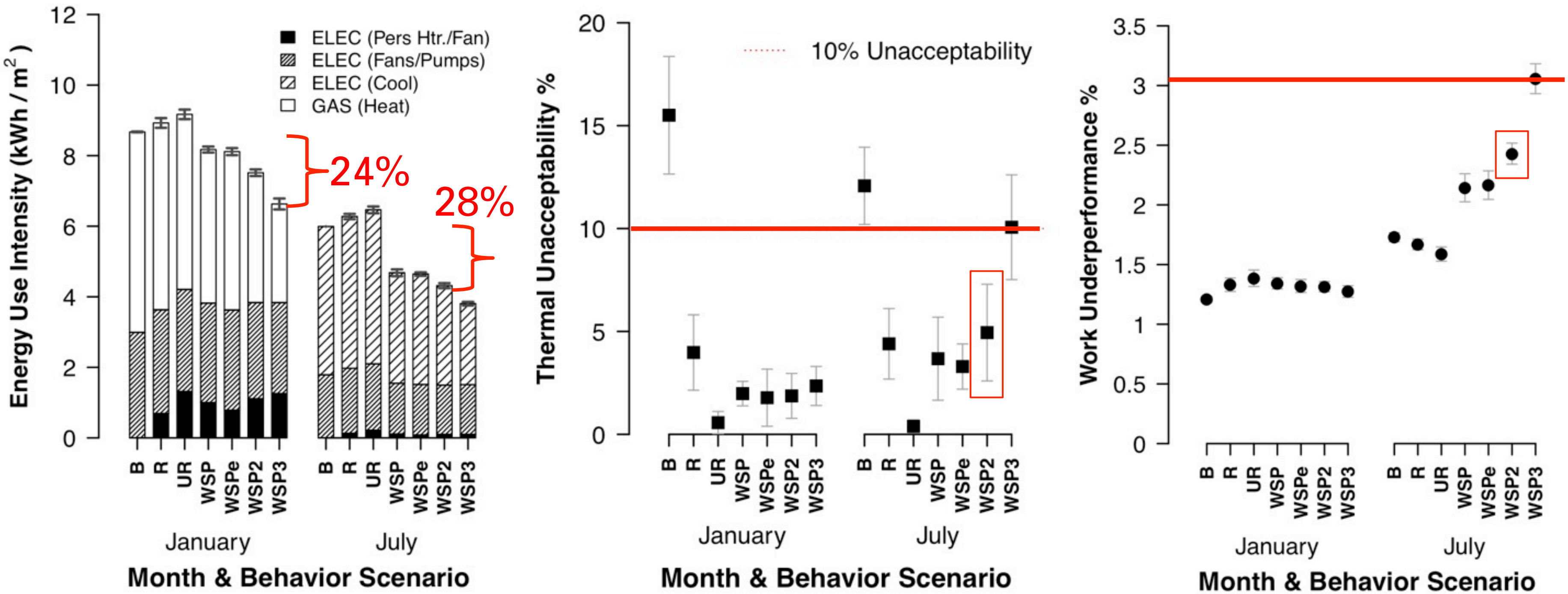
Wider set points look good from the energy and IEQ perspectives - to a point



Langevin et al, “Quantifying the human-building interaction”, Energy and Buildings, 2015

Local heaters look bad while fans look good from a financial perspective

- NPV1 – Energy $
- NPV2 – Energy + Carbon $
- NPV3 – Energy + Carbon + Productivity $

SEASON	NPV METHOD	BEHAVIOR SCENARIO B	R	UR	SPF	SPFe	SPF2	SPF3
Heating Season	*NPV1*	$0	-$13,986 *(+/- $1,810)*	-$23,363 *(+/- $1,884)*	-$13,121 *(+/- $925)*	-$10,106 *(+/- $866)*	-$10,352 *(+/- $813)*	-$6,190 *(+/- $1,226)*
	NPV2	$0	-$19,944 *(+/- $2,791)*	-$34,674 *(+/- $2,908)*	-$18,990 *(+/- $1,414)*	-$14,244 *(+/- $1,320)*	-$14,964 *(+/- $1,236)*	-$8,856 *(+/- $1,852)*
	NPV3	$0	-$52,001 *(+/- $21,333)*	-$80,912 *(+/- $27,630)*	-$54,150 *(+/- $69,401)*	-$43,586 *(+/- $19,862)*	-$42,786 *(+/- $19,778)*	-$26,061 *(+/- $20,394)*
Cooling Season	*NPV1*	$0	-$9,822 *(+/- $1,351)*	-$13,433 *(+/- $1,801)*	$20,454 *(+/- $1,801)*	$21,165 *(+/- $901)*	$27,400 *(+/- $1,351)*	$37,080 *(+/- $901)*
	NPV2	$0	-$12,807 *(+/- $2,102)*	-$18,425 *(+/- $2,803)*	$34,306 *(+/- $2,803)*	$35,412 *(+/- $1,402)*	$45,114 *(+/- $2,102)*	$60,176 *(+/- $1,402)*
	NPV3	$0	$2,832 *(+/- $26,825)*	$18,304 *(+/- $33,706)*	-$73,776 *(+/- $46,067)*	-$78,455 *(+/- $44,666)*	-$137,443 *(+/- $39,186)*	-$286,161 *(+/- $44,666)*

* 95 % prediction bounds italicized in parentheses

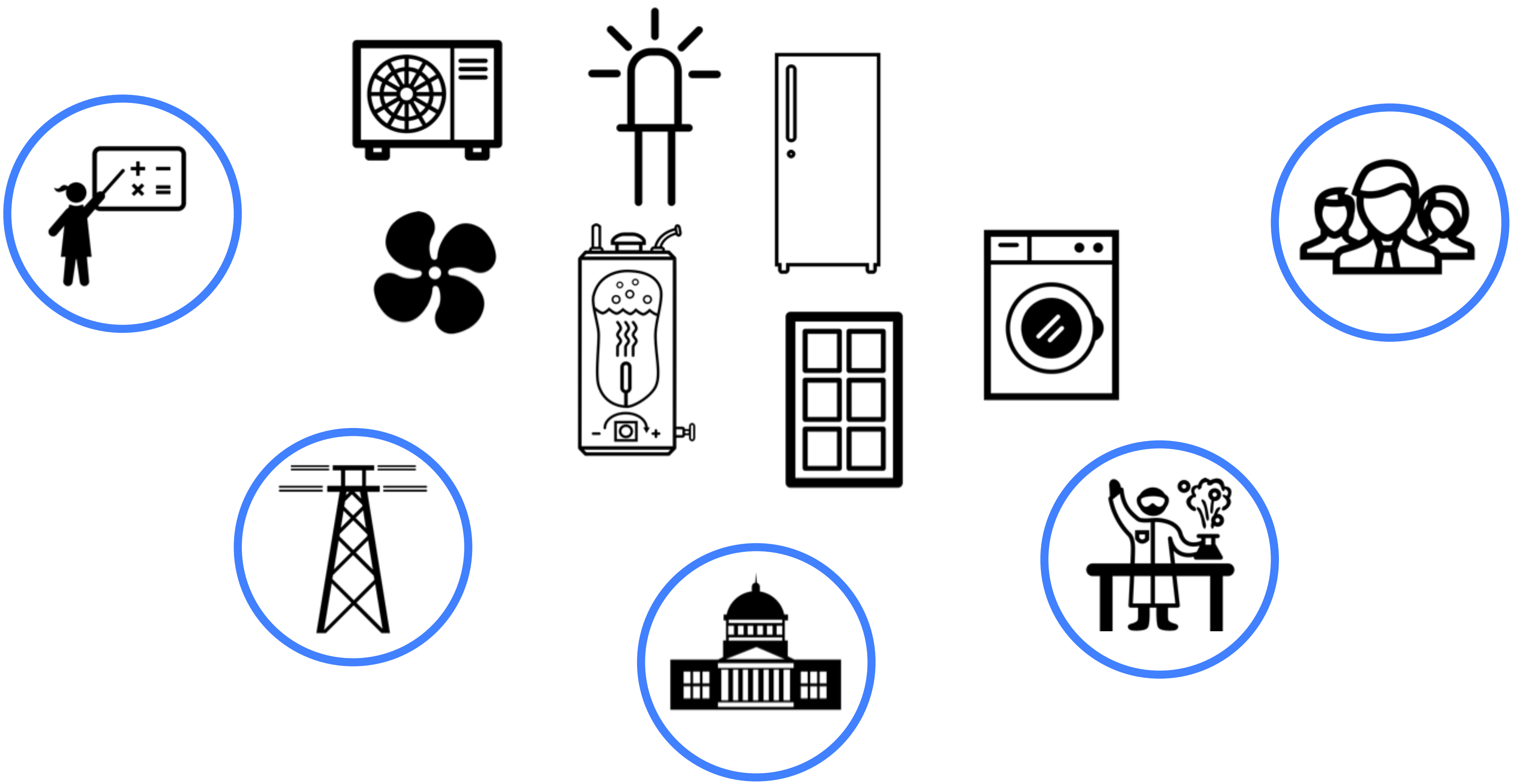
Langevin et al, "Quantifying the human-building interaction", Energy and Buildings, 2015

Part 2

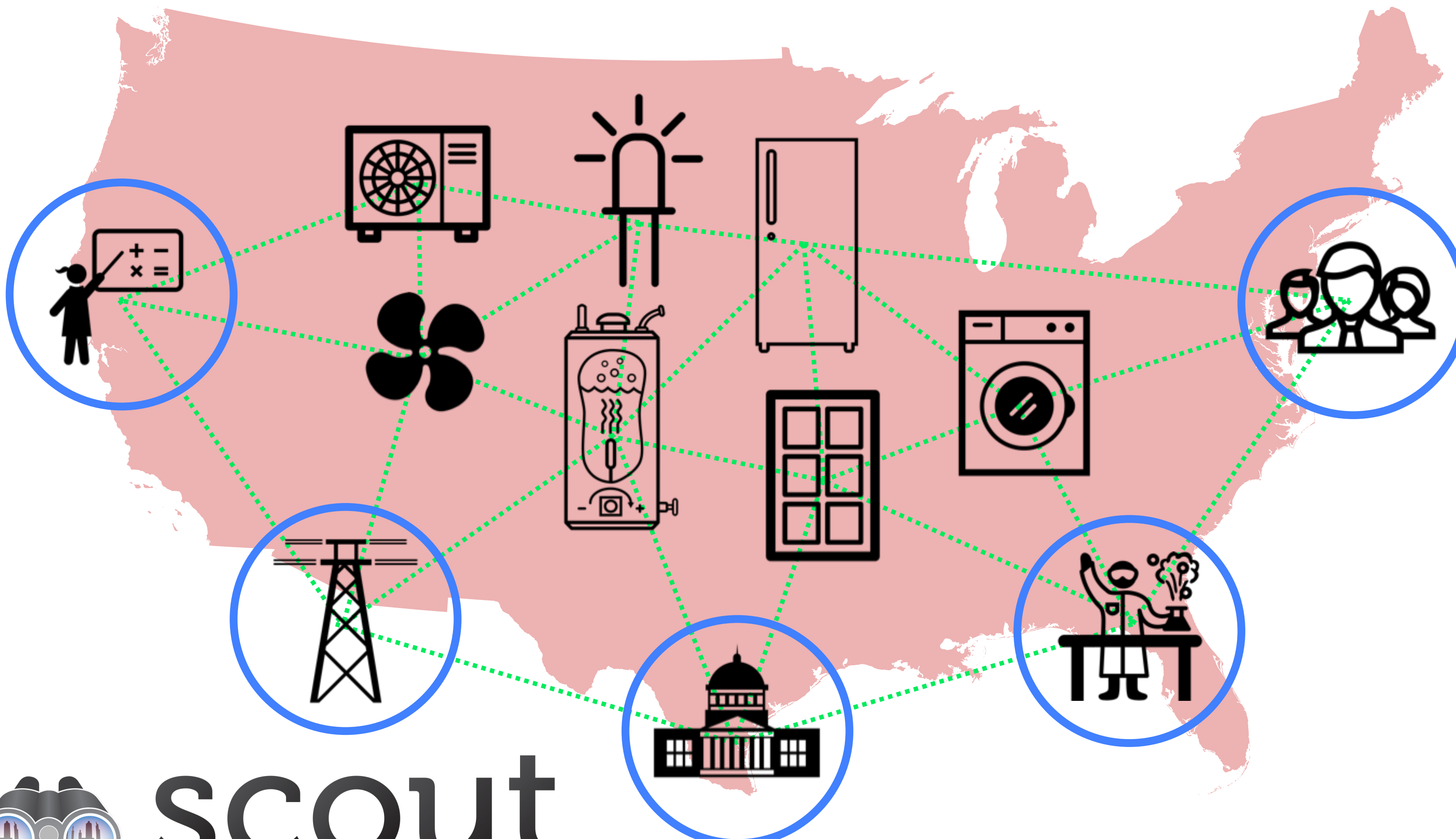
Scout: An impact analysis tool for building energy efficiency technologies

Post-doctoral work performed at the U.S. Department of Energy in collaboration with AAAS Fellow Dr. Chioke Harris under mentors Dr. Patrick Phelan and Dr. Amir Roth

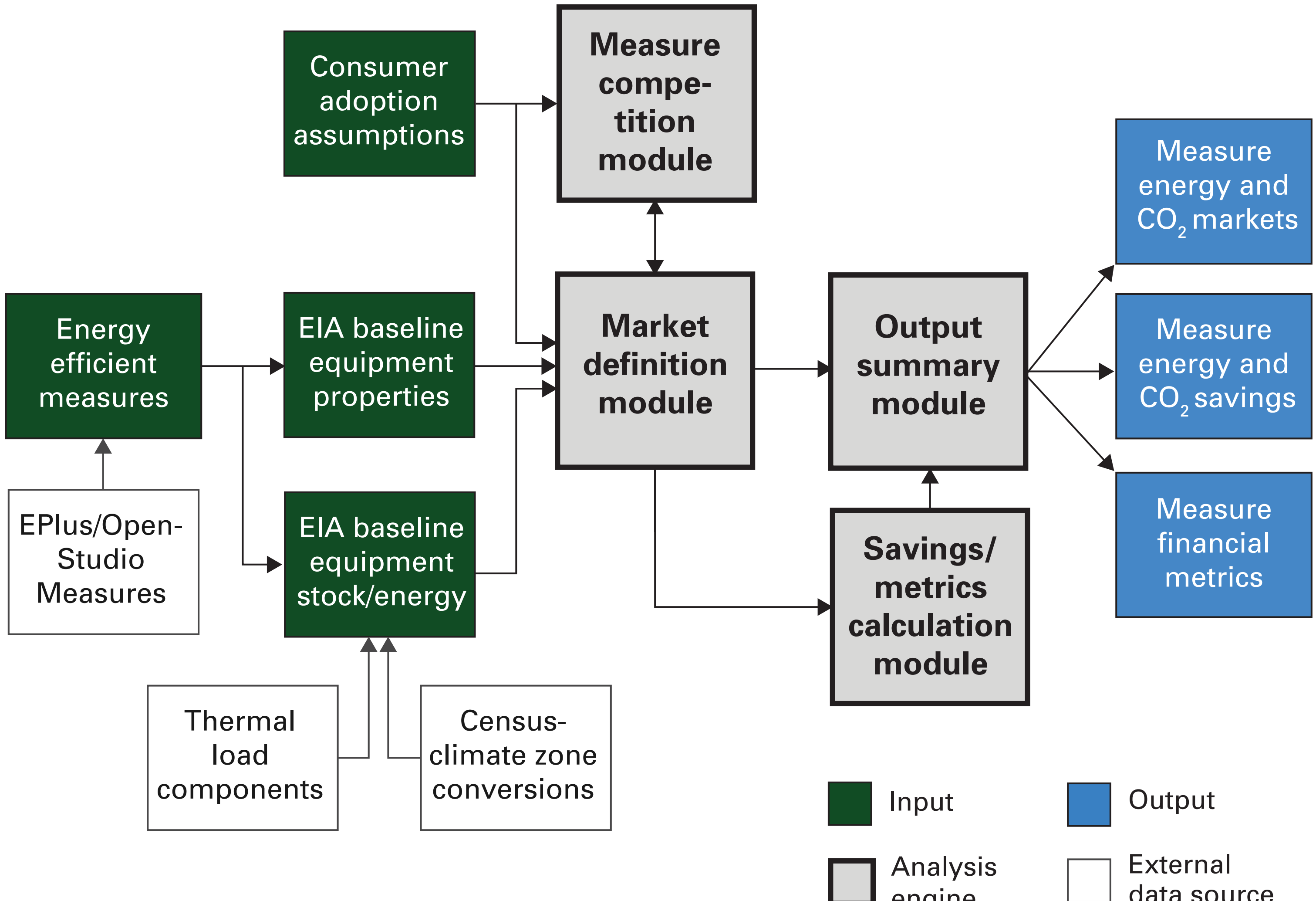
The problem: many efficient technologies, multiple perspectives



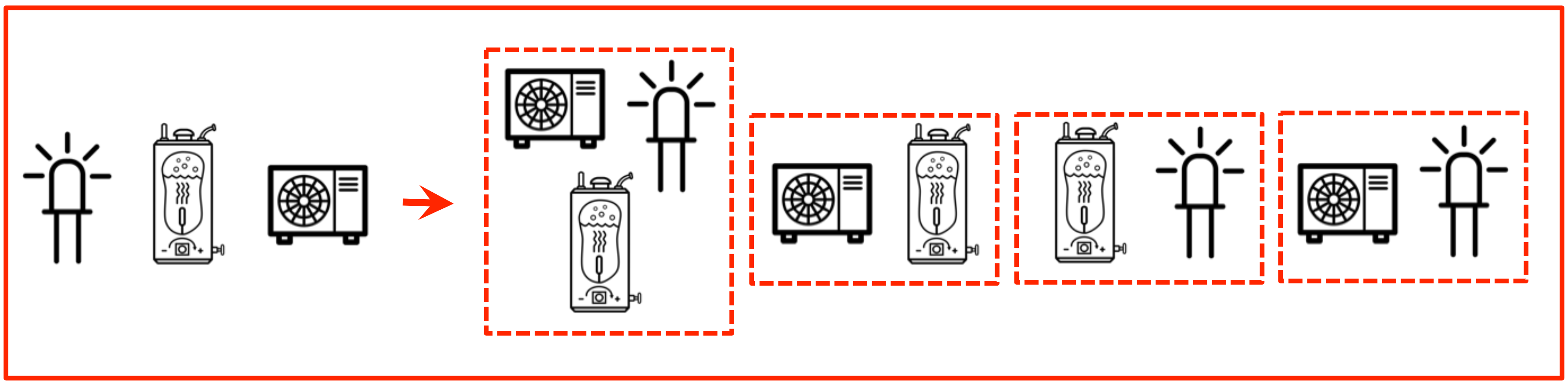
Scout establishes a common framework for efficiency measure impact estimation



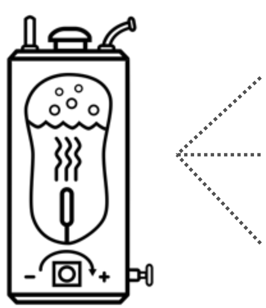
Scout applies individual efficiency measures across the U.S. building stock



Measures can be packaged and assigned input uncertainty



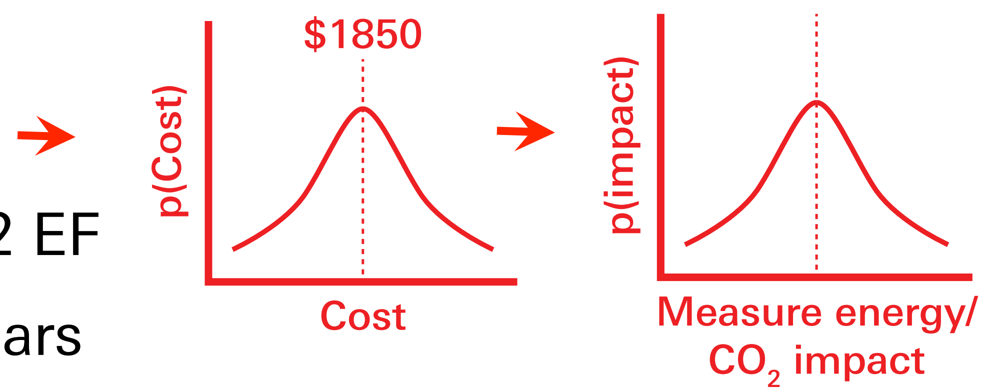
Compete individual and packaged measures



Cost: $1850

Performance: 2 EF

Lifetime: 13 years



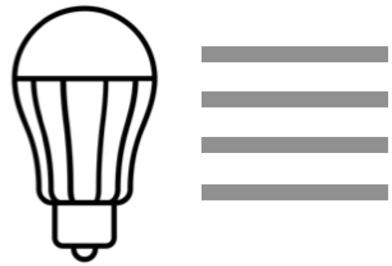
Measures apply to baselines drawn from EIA Annual Energy Outlook

Data reported for each year from 2009 to 2040

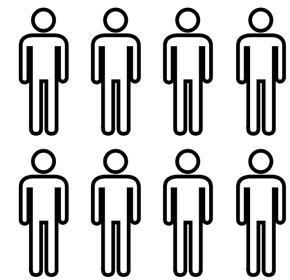
Energy Use

Building Stock

Equipment Characteristics

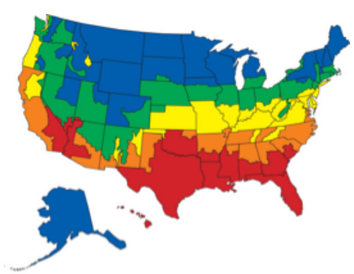


Adoption Model Parameters



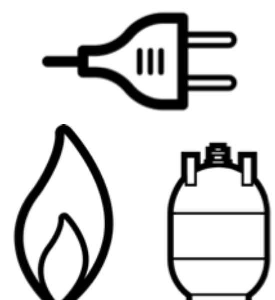
Building Type

Climate Zone



End Use

Fuel Type

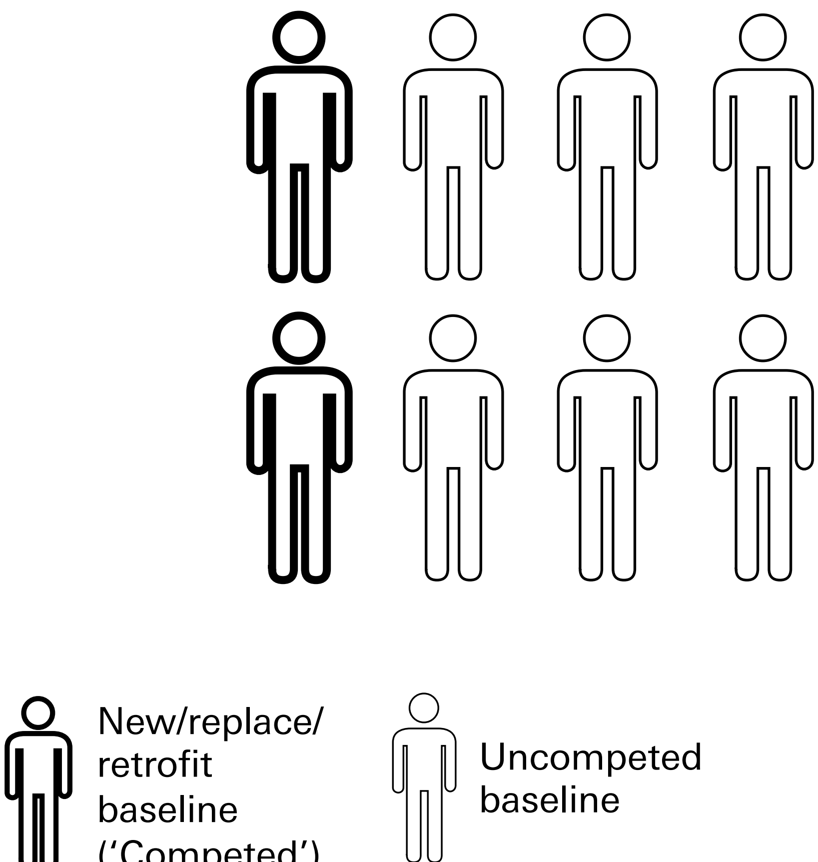


Technology

Baseline data define building and equipment stocks and flows

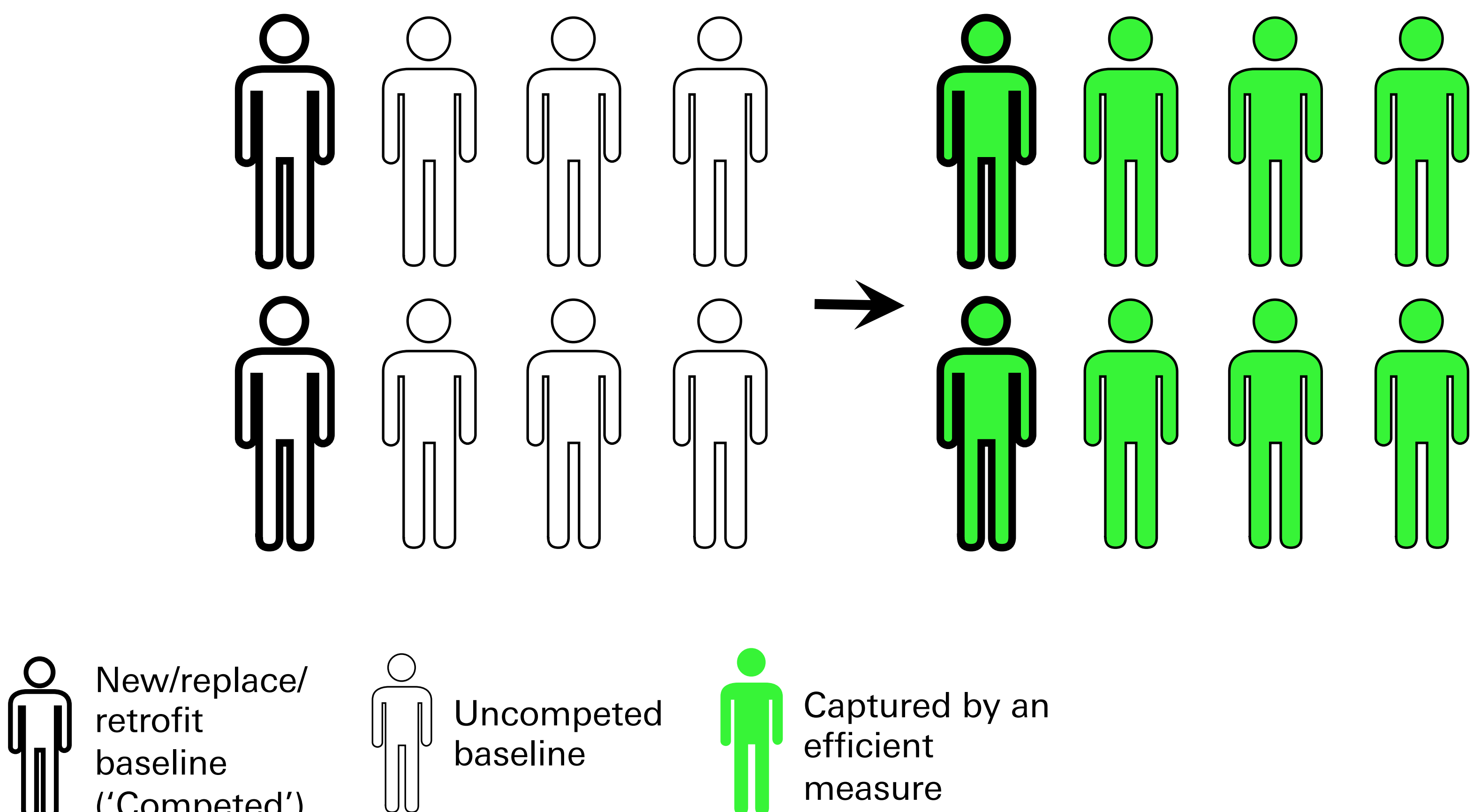
Measures diffuse into markets under three adoption scenarios

Total baseline market (Year Y)



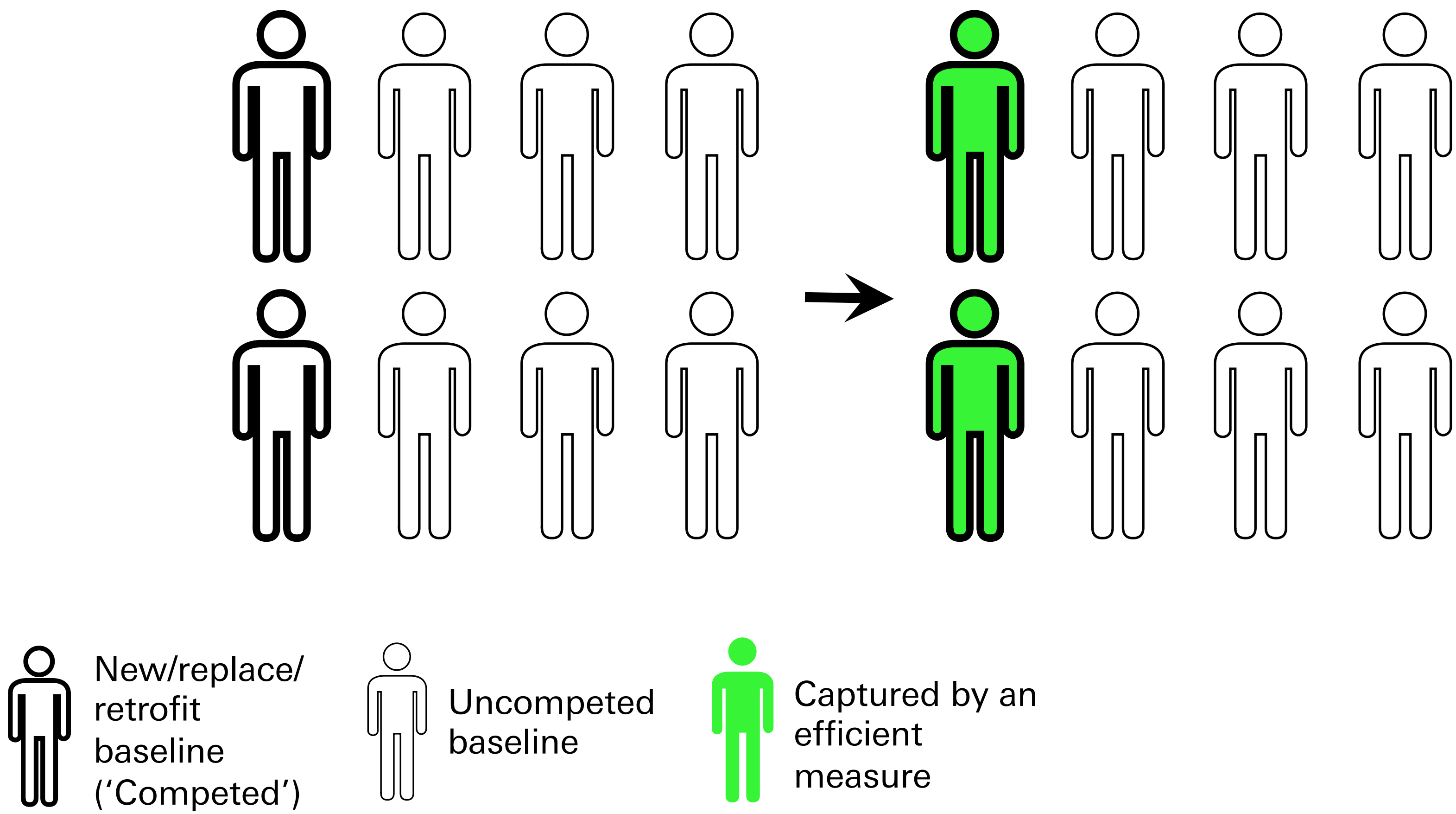
Measures diffuse into markets under three adoption scenarios

Technical Potential Scenario: Total market fully captured



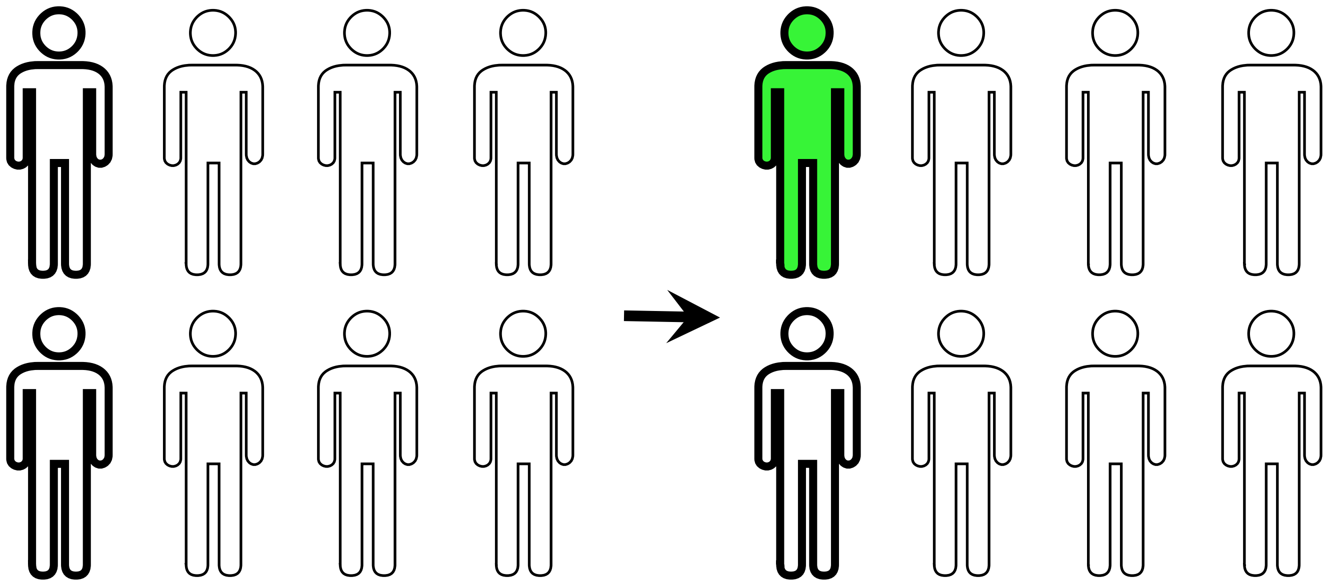
Measures diffuse into markets under three adoption scenarios

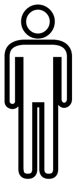
Maximum Adoption Scenario: Competed market fully captured



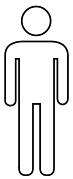
Measures diffuse into markets under three adoption scenarios

Adjusted Adoption Scenario: Competed market partially captured

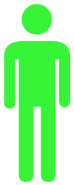




New/replace/ retrofit baseline (‘Competed’)

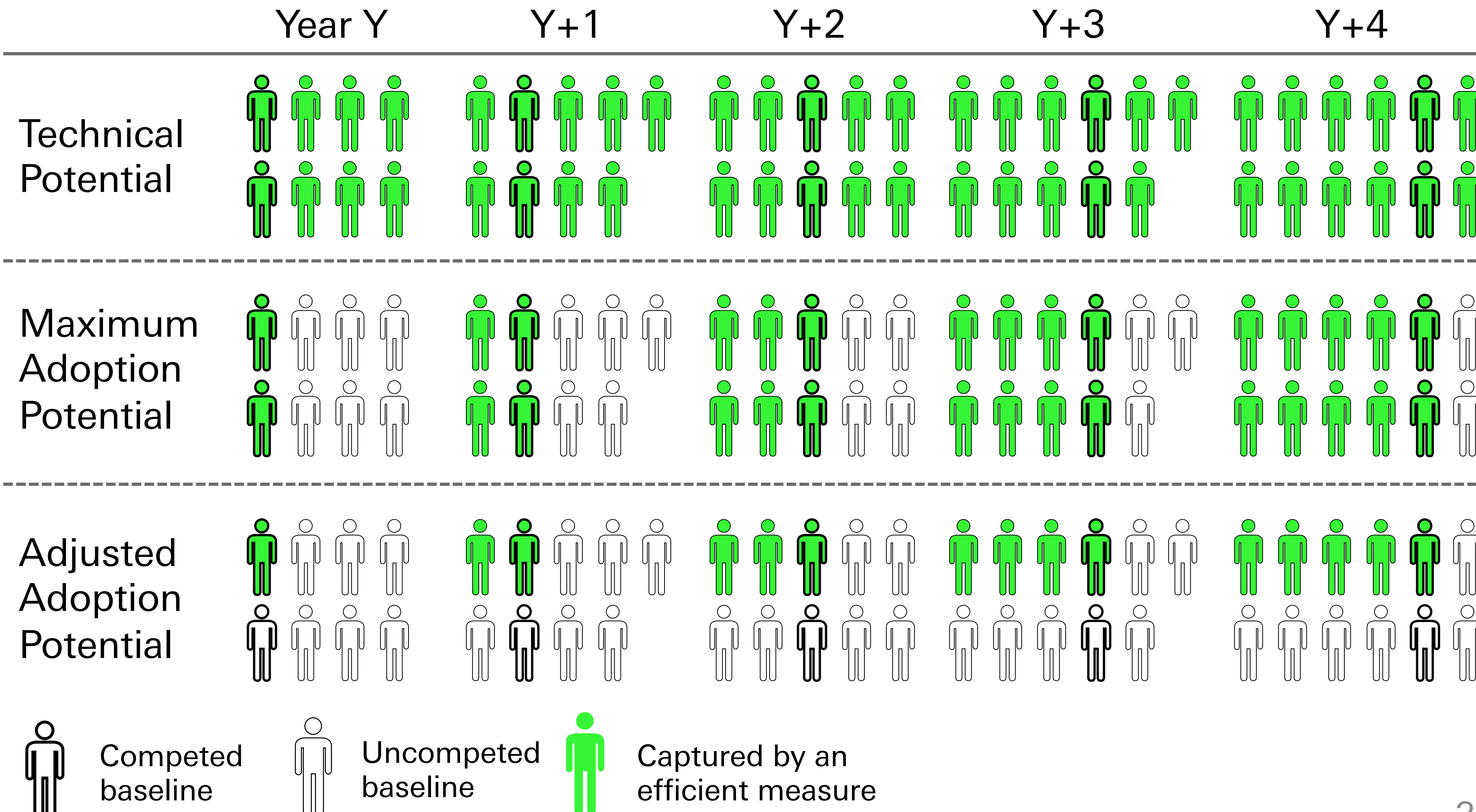


Uncompeted baseline

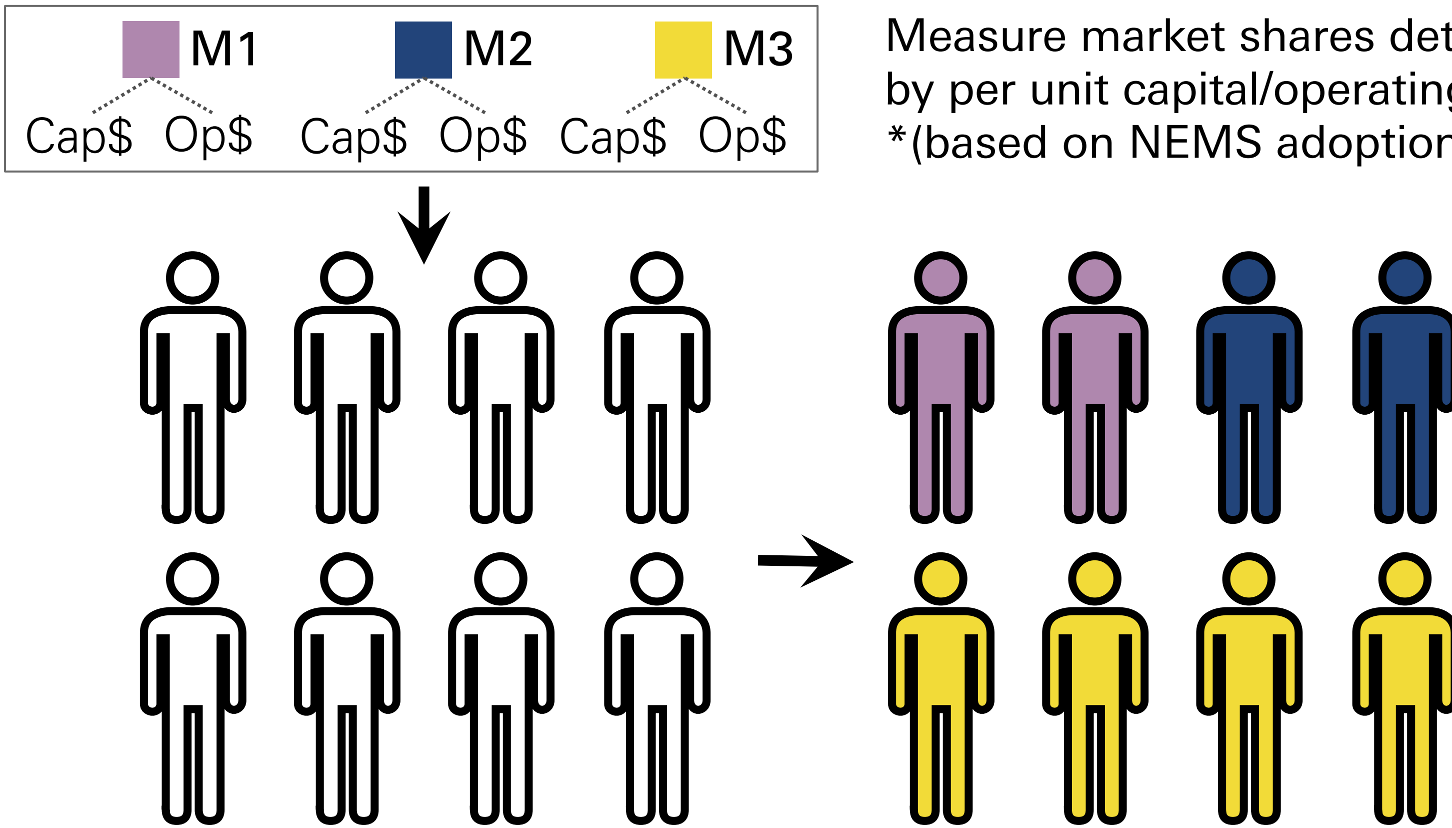


Captured by an efficient measure

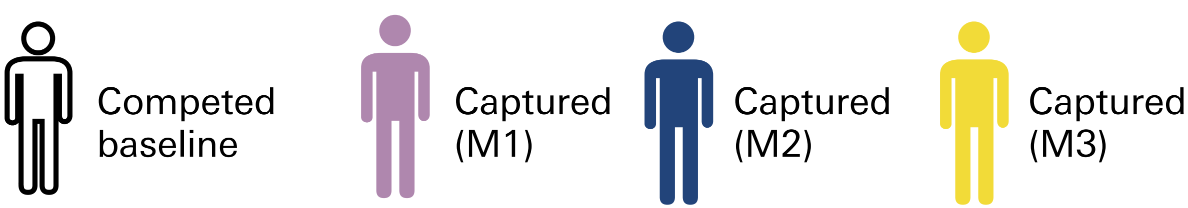
Adoption scenarios determine measure diffusion rates over time



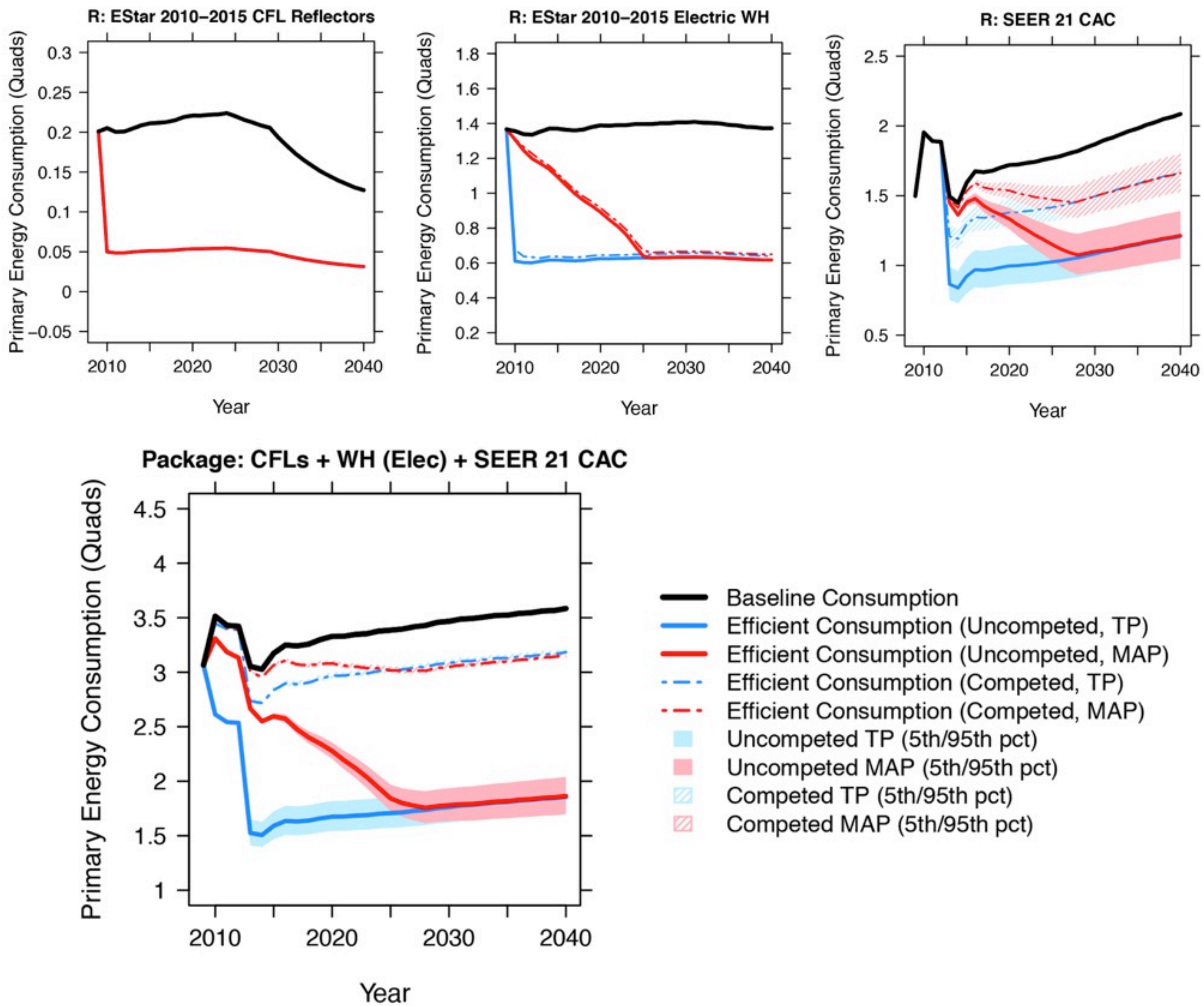
Competing measures are attributed shares of the competed baseline



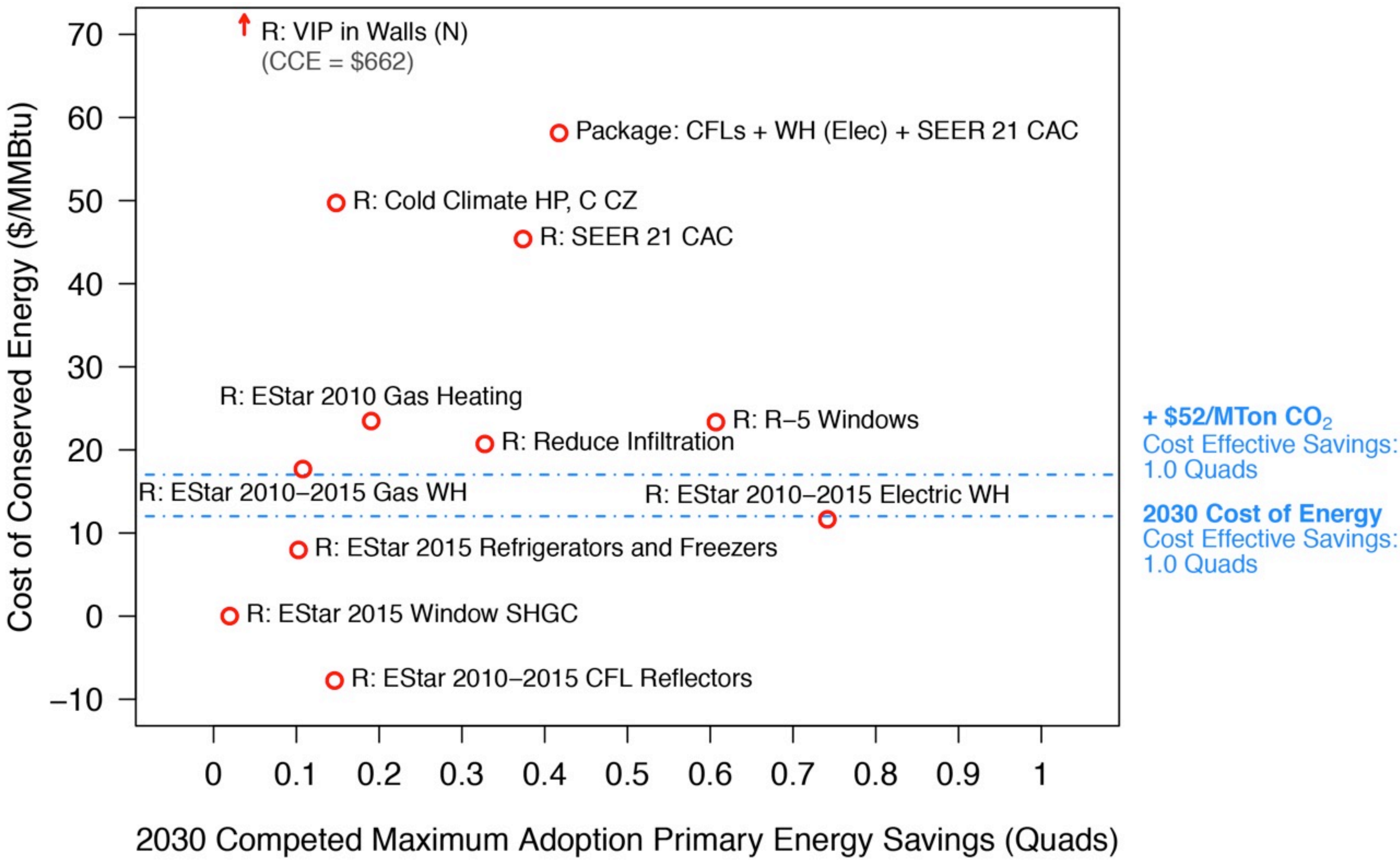
Measure market shares determined by per unit capital/operating costs *(based on NEMS adoption models)



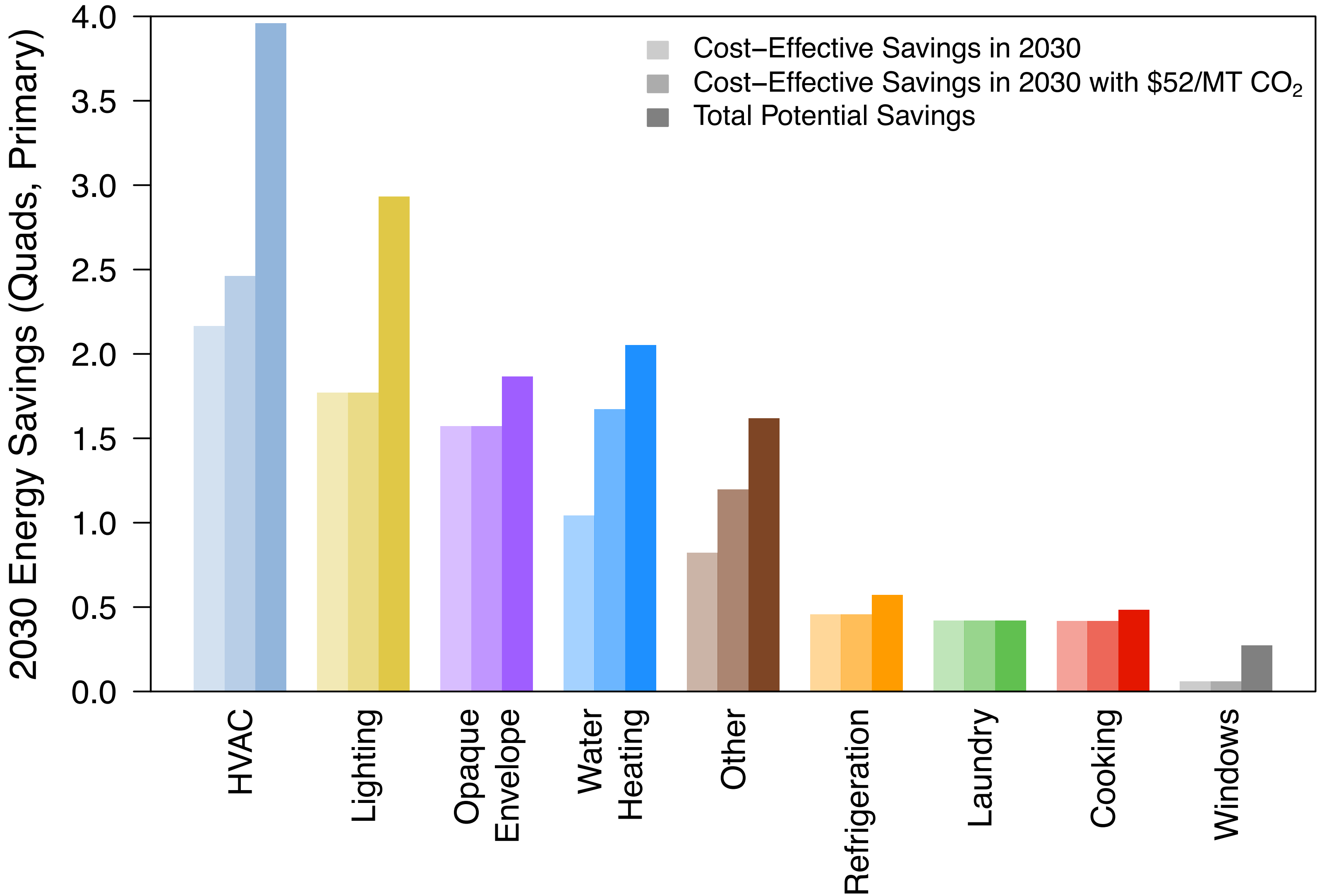
Results can show the effect of package measures, uncertainty



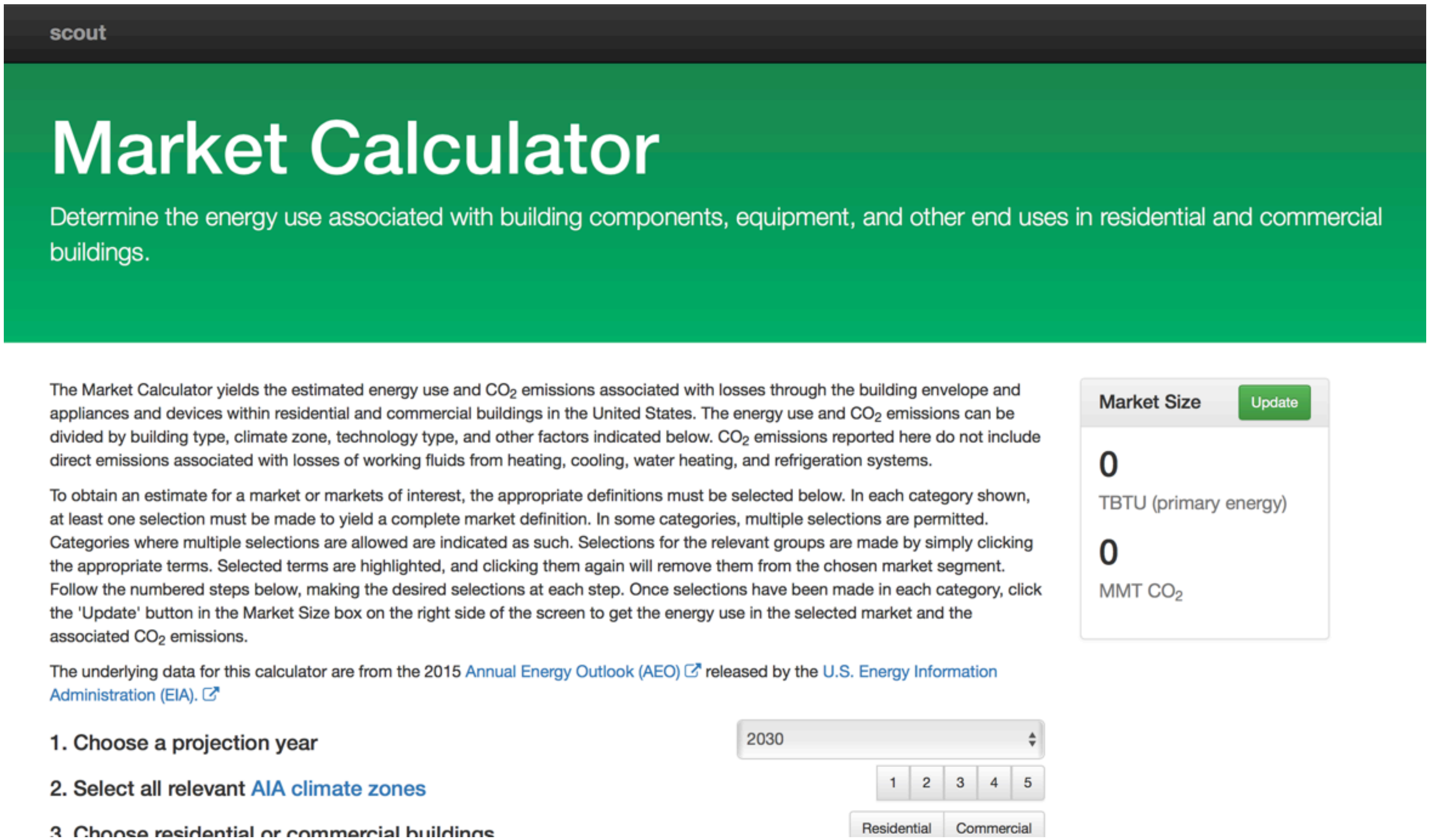
Measure cost-effectiveness and impacts vary widely



End use potential impacts are influenced by the measure portfolio



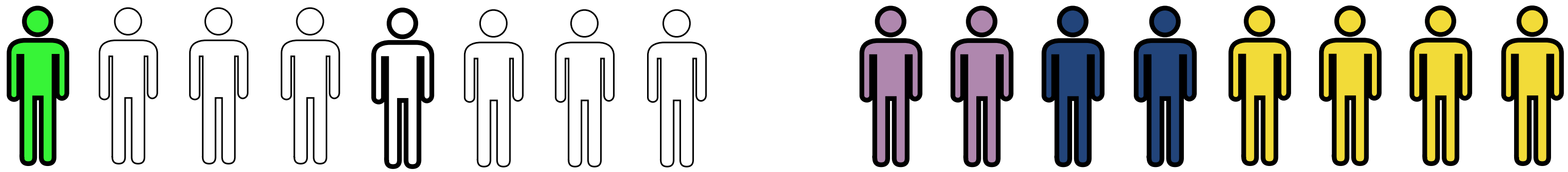
Interactive web tools using model input data and results are forthcoming



https://trynthink.github.io/scout/calculator.html

Multiple areas have been identified for future development

Improved representation of consumer adoption dynamics



Modeling potential for peak demand reductions

Non-energy benefits

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Icon attributions

Slide 1: United States (Bohdan Burmich)

Slide 20: LED (Nikita Kozin); Water heater (Michael Thompson); Air conditioning unit (Arthur Shlain); Fan (Edward Boatman); Refrigerator (shashank singh); Washing machine (Ed Harrison); Window (Arthur Shlain); Teacher (TukTuk Design); Utility tower (Maurizio Fusillo); Capitol building (Kelcey Hurst); Lab scientist (Edward Boatman); Business team (lastpark)

Slide 24: Energy (Edward Boatman); Buildings, Mosque, House (Creative Stall); School (Tran); Plug (Arthur Shlain); Flame (Samuel Q. Green); Propane Tank (Carlos Salgado); Fluorescent Light Bulb (Matt Brooks); Light Bulb (Marco Galtarossa); LED bulb (Alex Podolsky)

Slide 26: Figure (Alexander Smith)

Slide 36: Solar panels (Adam Terpening); Turbines (Creative Stall); Power Plant (Iconathon); Clock (Karen Tyler); Faucet (Carla Gom Mejorada);

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